Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR)

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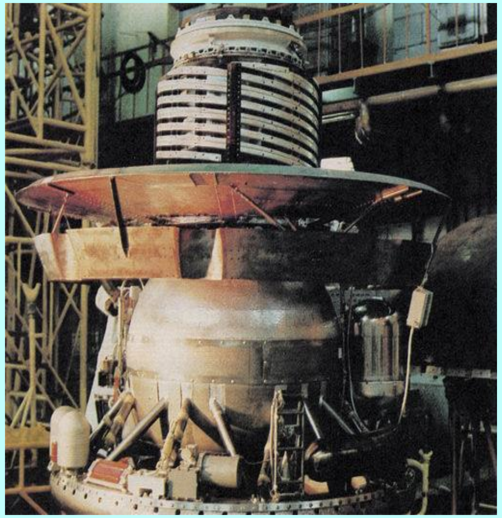
Types of Venus Missions

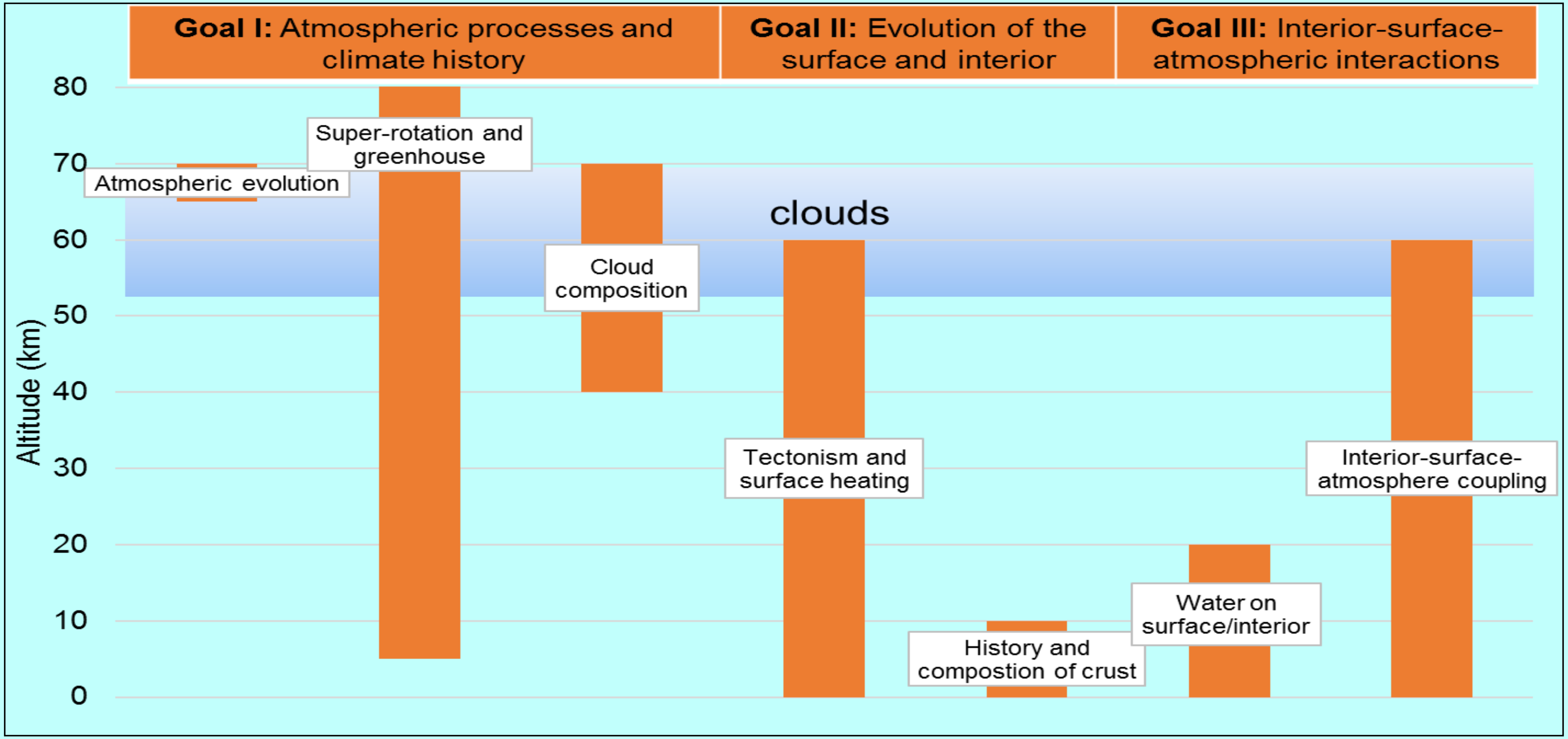
- **Orbital missions**: Russian Venera (4-13) series [4], the US Magellan and the European Venus Express
- **Balloon Missions**: Several missions have been implemented successfully, e. g., the Russian "VEGA" missions (1985).
  - Two balloons of 3.5m diameter super-pressure helium balloons with 7-kg instrumented payload were deployed into the atmosphere, and floated for 48 hours at about 54 km altitude.
  - Powered by primary batteries, the VEGA balloons operated only in the relatively benign temperature regime of the cloud-level, and did not attempt to probe into the higher temperature regions below the clouds.
- **Surface missions (Lander/Surface Probes)**: Probes from the Venera series, Vega program and Venera-Halley probes.
  - Successfully landed on Venus and transmitted images of the Venus surface.
  - Lasted only <2 h due to the failure of batteries and electronics, even with extensive thermal insulation, phase-change materials and similar heat sinks.

VEGA balloon (22 kg)



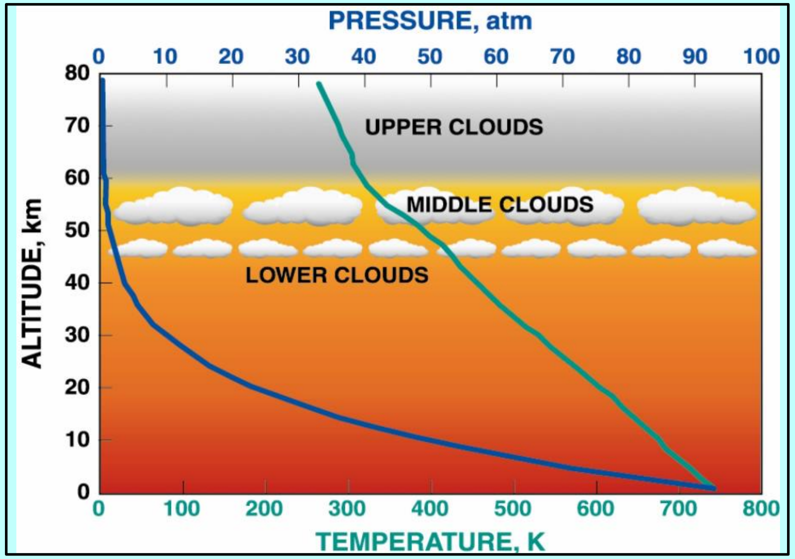
VEGA lander (750 kg)

Science Capabilities of Venus Variable Altitude balloons

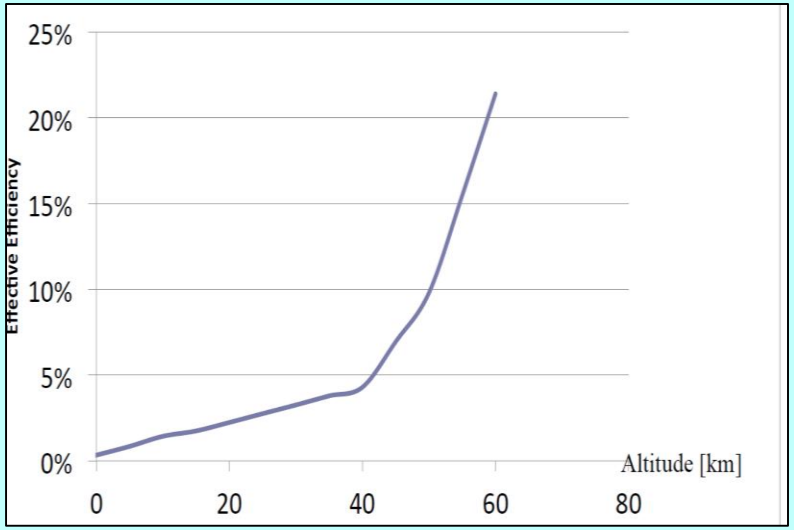


Challenges of Power Technologies for Venus Missions

- Extreme environment : High temperature and Pressure.
- Conventional long-duration power technologies, such as solar array and Radioisotope power systems are challenging
  - Reduced solar flux below the clouds and at the surface:
    - ~2600 W/m^2 (or roughly twice that of Earth's solar flux) at high altitudes and ~9 W/m^2 at the surface.
    - Need Energy Storage for load levelling and nighttime operations.
  - RPS could be even more challenging
    - The current Multi-mission Radioisotope Thermoelectric Generator (RTGs) is not capable of operating at 90 bar pressure and a +465°C heat sink.
    - Dynamic RPS are promising but significant development is needed and also requires an energy storage device for load levelling
- A new power generation and energy storage approach is required to enable an extended exploration of the Venus atmosphere and near-surface environments.



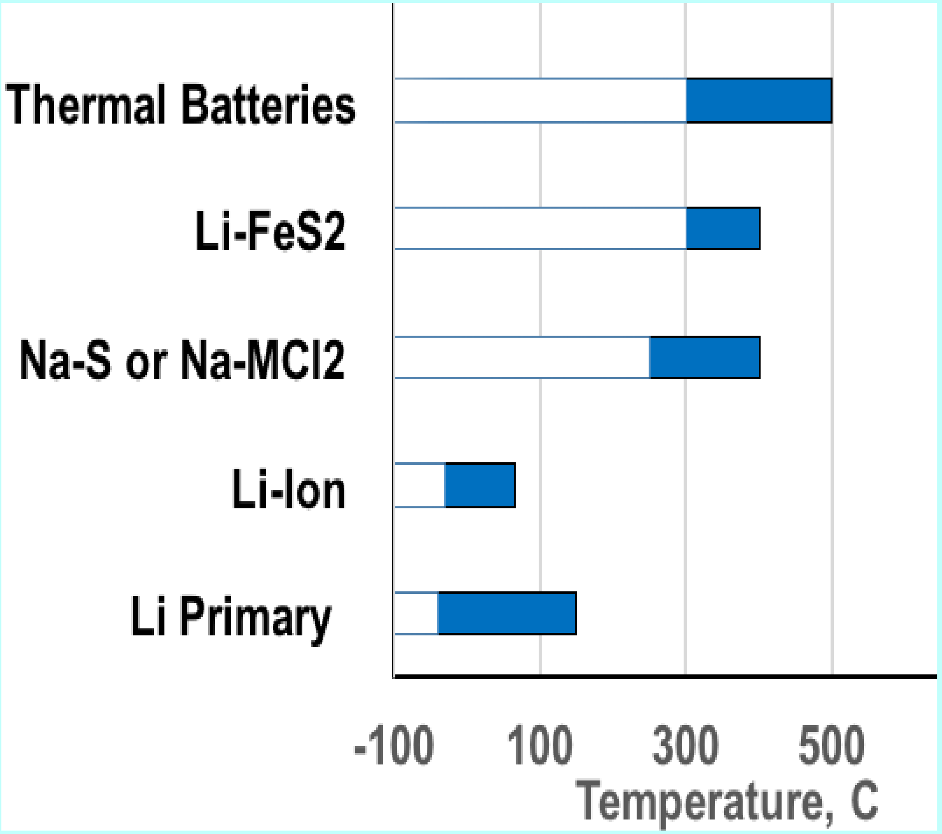
Venus temperature and pressure vs. altitude



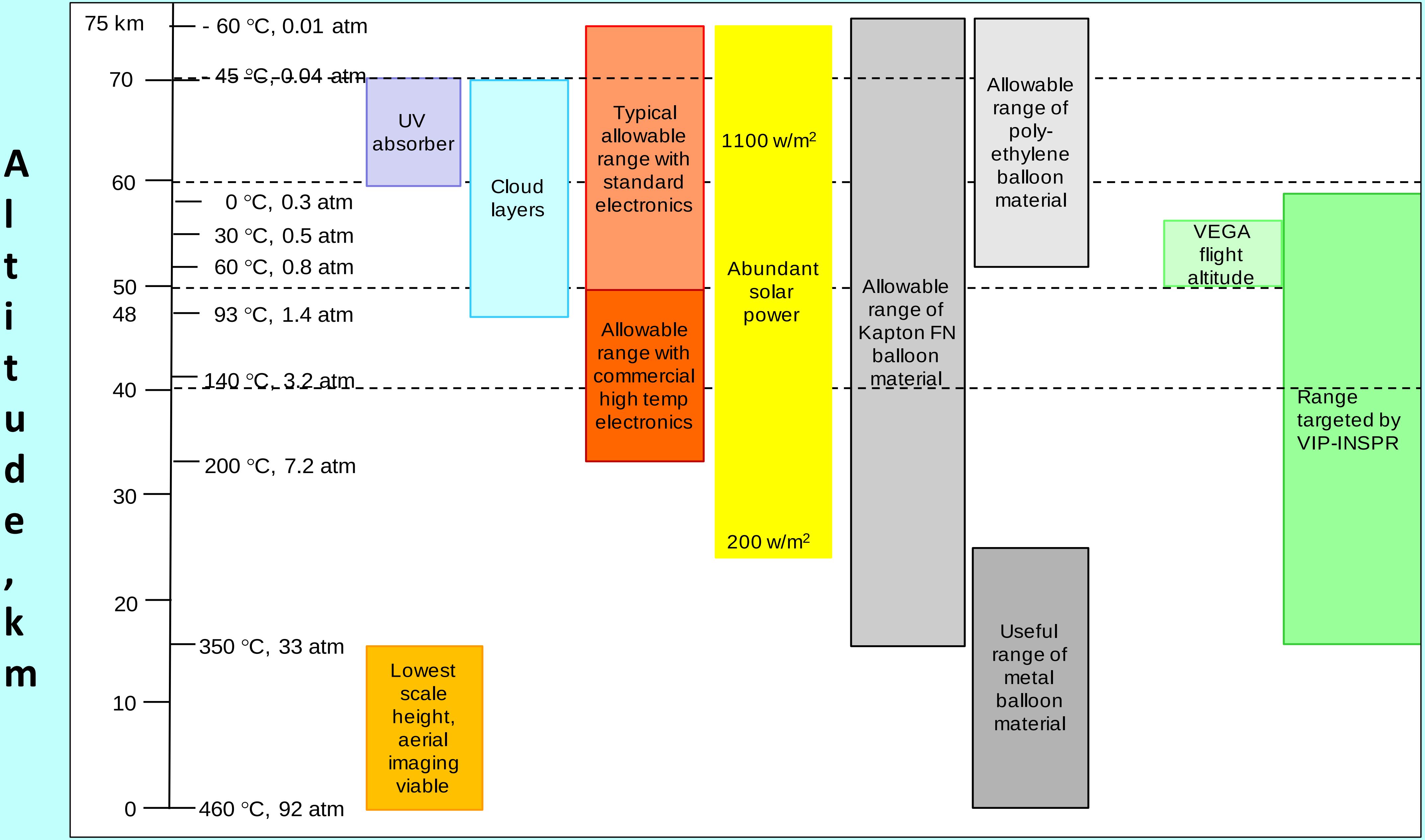
Triple junction solar cell efficiency vs. altitude

Battery Options Non-Existent

- There is no battery system that is thermally stable over 55-15 km (25-300^{o}C)
  - Li-ion batteries: Not stable above 70C.
  - Li primary batteries (Li-CF_X, Li-$SOCl_2$): Not stable above 150C
  - High temperature sodium rechargeable batteries do not function below 250C
- Even with thermal management, the life is limited to a few hours.



Venus Environments and Balloon Technologies



Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR)

High Altitude Balloon

- Abundant solar power
- Bring stored H_2 (metal hydride) and O_2 (compressed gas cylinder)

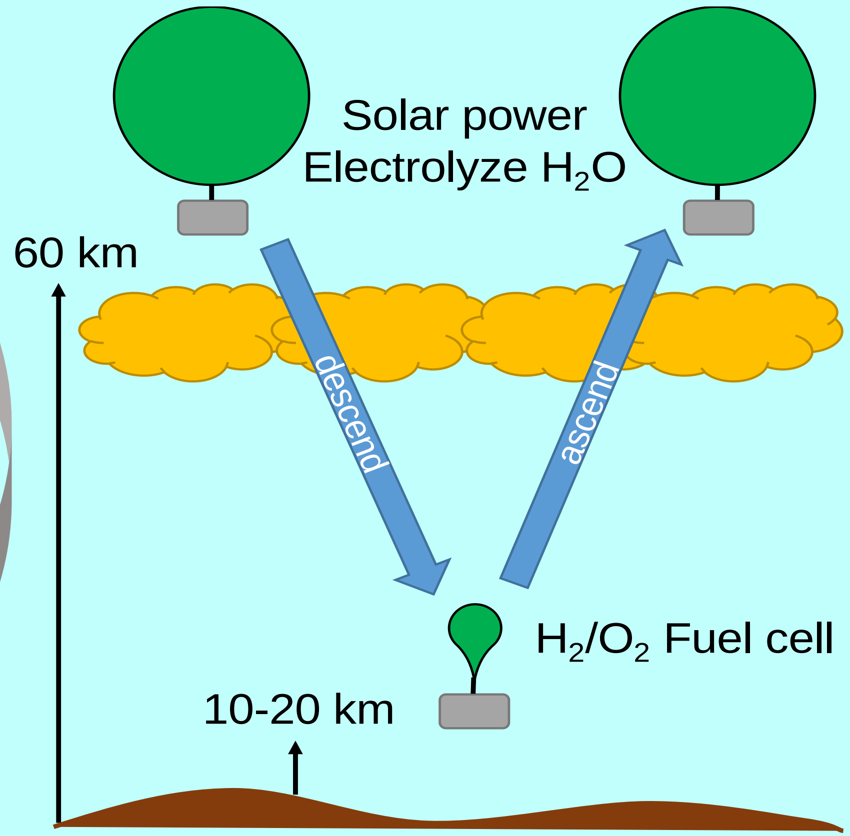
Descend below clouds

- Store ~100 g H_2 from balloon in metal hydride
- Operate on solid oxide fuel cell (SOFC)
- Store H_2O byproduct

Ascend above clouds

- Release H_2 back into balloon
- Operate on solar power
- Electrolyze H_2O back into H_2 and O_2

Repeat



- Generation of hydrogen and oxygen at high altitude from *in situ* resources, i.e., solar energy and sulfuric acid/water from the Venus clouds and generation of power at low altitudes utilizing these resources in a high temperature fuel cell.
- In addition, the hydrogen generated at high altitudes will also be used as a lifting gas to navigate the probe across the Venus clouds for extended durations (not limited by power).

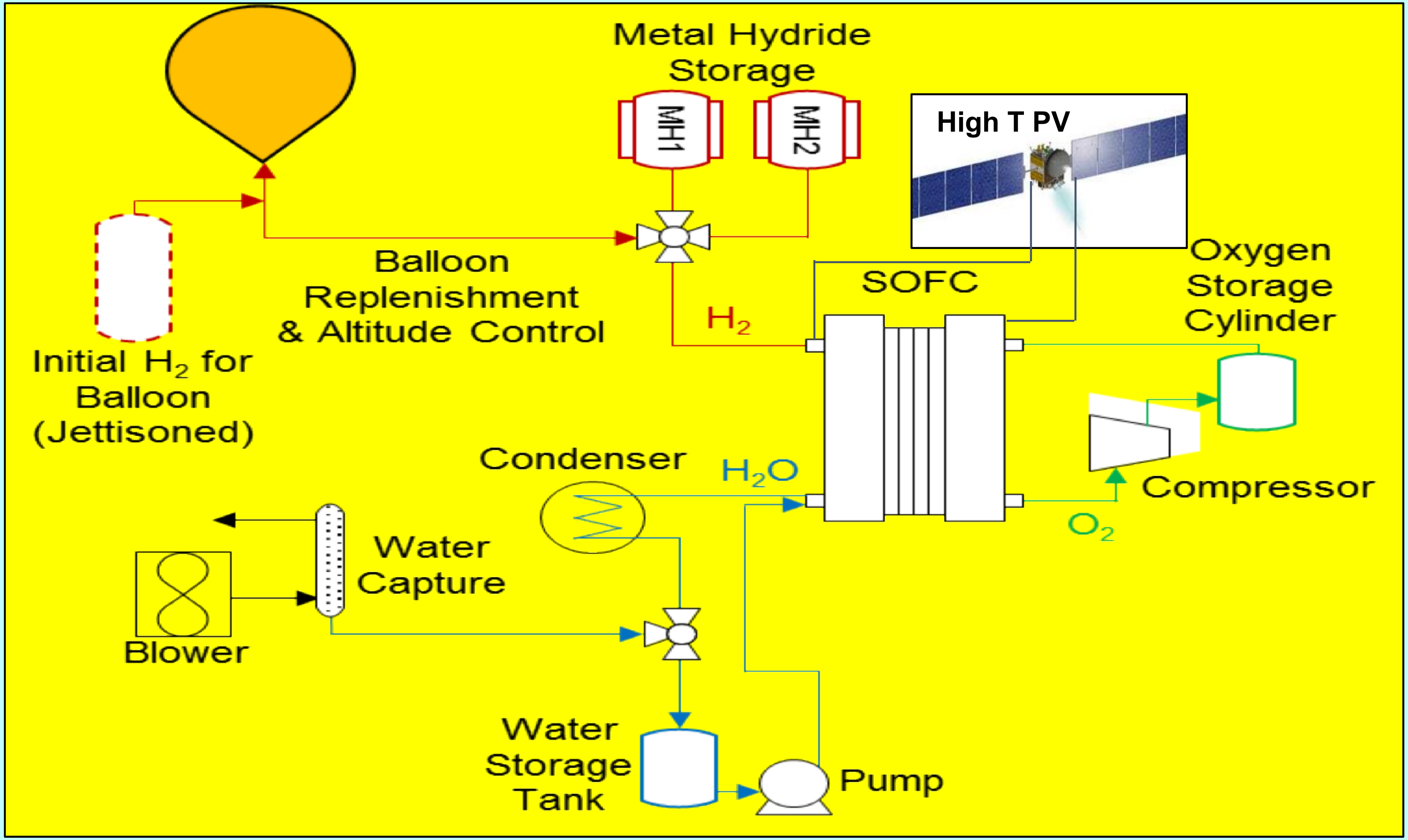
VIP-INSPR's Component Technologies

- A Reversible Solid Oxide Fuel Cell (RSOFC) for electrolysis at high altitudes and power generation at low altitudes.
- High temperature tolerant solar array to provide power to the balloon and to the RSOFC to generate H_2 and O_2 at high altitudes
- Harvesting in-situ resources (H_2SO_4 or H_2O) in the upper atmosphere for electrolysis (generation of H_2 and O_2)
- Hydrogen storage in a multi-system wide-temperature metal hydride (MH) (absorption at low T and desorption at high T)
- Electrochemical compression and storage of oxygen
- Balloon altitude control system using MH to store H2 for descent to low altitudes for subsequent power generation.
- Balloon design for 55-15 km on Venus

What is Novel in the VIP-INSPR

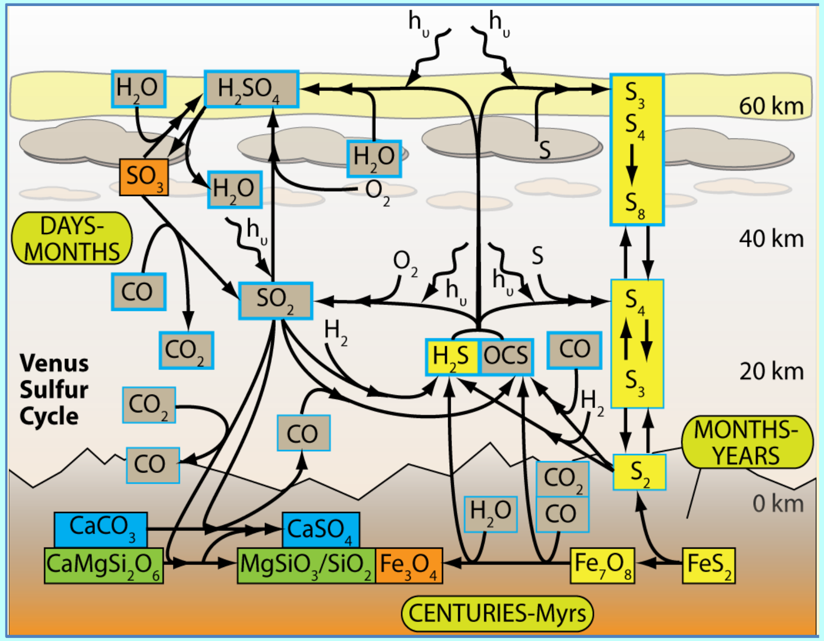
- Can potentially cycle between high and low altitudes and perform scientific studies above and below the Venus clouds, with detailed compositional studies within the clouds as the probe ascends/descends.
- By virtue of its ability to utilize resources for power generation and navigation, this probe could have an extended mission life.
- There would be several firsts in this novel architecture
  - First to utilize Venus in-situ resources to enable sustained exploration
  - First to use a solid oxide fuel cell as a power source at low altitudes on Venus
  - First test platform for high temperature low altitude Venus missions.
  - First to use a hydrogen balloon on a planet; thus far, only helium was used.
  - First to use in-situ generated hydrogen for ballooning.
- Thus, the VIP-INSPR is a unique low-altitude power generation system for Venus mission concepts and could be more efficient and less expensive than RPS alternatives. This architectural concept may possibly be extended to other planetary bodies for power and navigation.
- The reversible solid oxide fuel cells has significant terrestrial value, as evident from recent DOE interest.
  - SOFCs are being developed to produce electricity from natural gas, and SOECs for the production of H_2.

Venus Probe with In-situ Power



Science Value – What VIP-INSPR could mean to Venus

- Durable Variable Altitude Balloons (VABs) will allow us to
  - Perform long-term measurements across Venus clouds,
  - Determine the chemical species and isotopes underneath the clouds
    - *In situ* measurements of chemical composition of the atmosphere and abundances of gases SO_2, CO, COS, H_2O, NO_2, HCl, HF, their isotopologues and isotopic ratios D/H, $^{13}C/^{12}C$, $^{18}O/^{17}O/^{16}O$, $^{34}S/^{33}S/^{32}S$ as a function of altitude and latitude.
    - Determine the content and isotopic composition of light and noble gases in the atmosphere. Verify CO_2 and N_2 gradient at altitudes below 65 km.
  - Transport to different longitudes on the planet and measure atmospheric flow patterns, especially with the altitude control,
  - Probe the interior structure through close-range imaging,
    - Characterize surface structure and morphology at a scale of 100-10 m/pixel from 15 km.
    - There is a definite value (order of magnitude improvement in spatial resolution) in IR observations from below the clouds, compared to high-altitude balloons.
    - Surface topography: We can possibly use Lidar below the clouds for topography as there would be less scattering.
  - Investigate the seismic activity from acoustic measurements at various altitudes. Determine the composition, chemistry, greenhouse, photochemistry, origin and evolution of the atmosphere, dynamics, atmosphere-surface interaction.

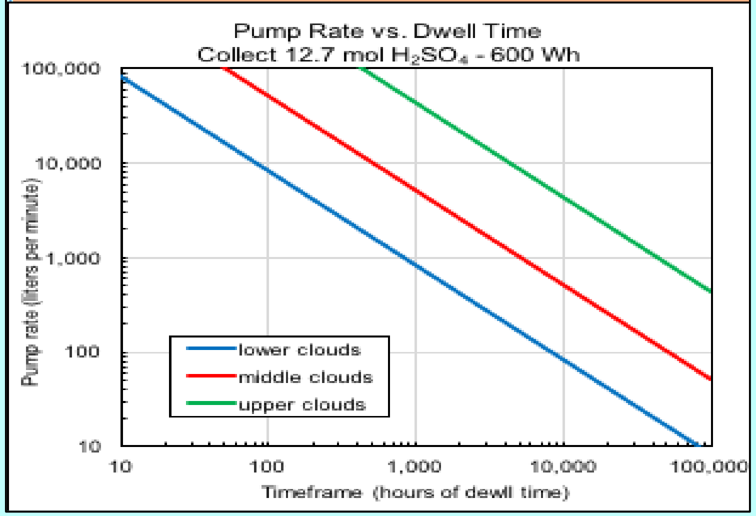


Intriguing chemical process in the Venus atmosphere

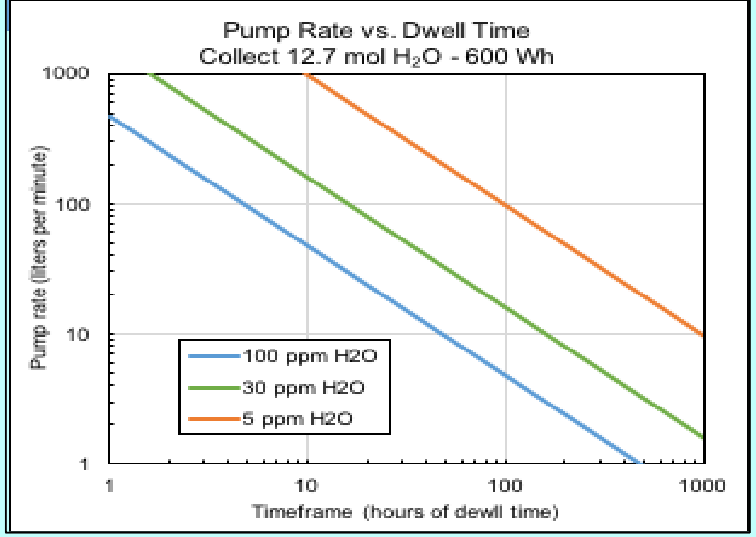
Harvesting H_2SO_4/H_20 from the Venus Clouds for Electrolysis

- Clouds on Venus are primarily composed of H_2SO_4 with droplets ranging from 0.4 -8 µm with 10-1500 droplets/mL, which could be captured using a high surface area mesh/film, using a pump or blower to move the cloud over the capture device.
- The total volume of atmosphere required to collect 12.7 moles of H_2SO_4 was estimated based on Knollenberg's 1980 paper.
- There is also a considerable amount of water vapor (~100 ppm) below 65 km. Even at the lowest estimate of 5 ppm H_2O, the total volume required for 12.7 mol H_2O is significantly lower than the highest estimate for the amount of H_2SO_4 in the clouds
- A comparison between pump rate and dwell time for water (vs H_2SO_4) shows reduced collection times. Using water is much simpler than using H_2SO_4 because there are no sulfur compounds present and also no decomposition reactions

	lower clouds	middle clouds	upper clouds
H_2SO_4 Concentration (mol/L):	4.9×10^{-9}	4.1×10^{-8}	2.6 x 10

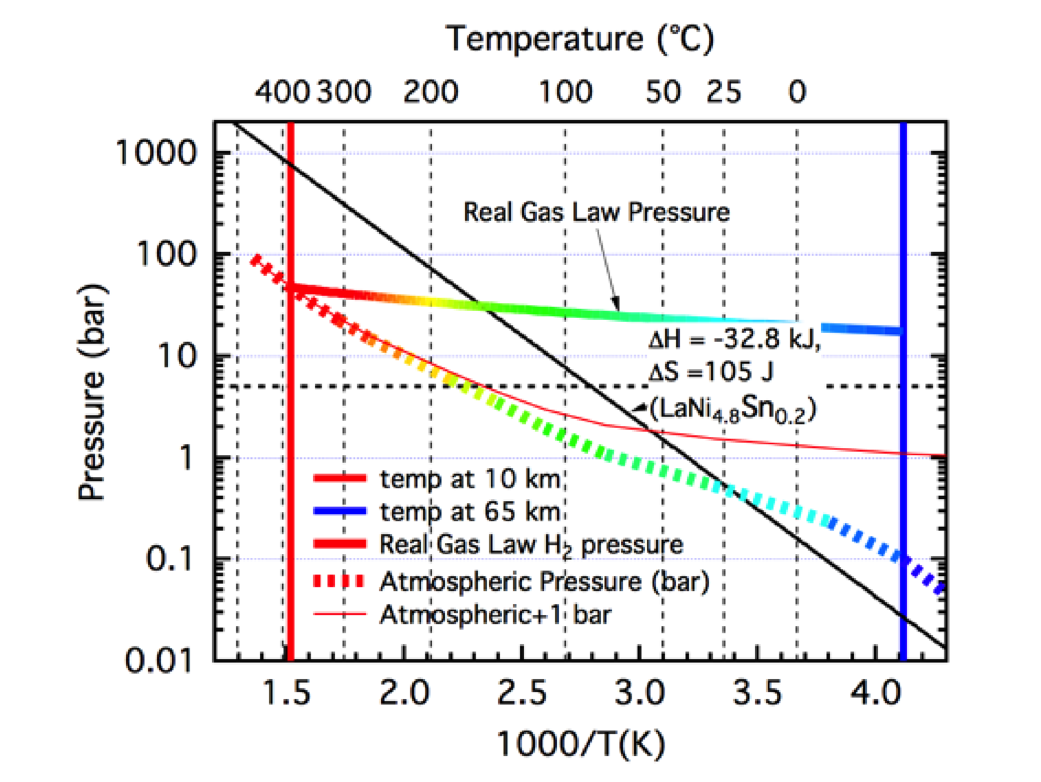


	lower estimate	middle estimate	upper estimate
H_2O Concentration (ppm):	5	30	100
Volume required (L):	5.7×10^5	9.5×10^4	2.8×10^4



Hydrogen Storage Using Metal Hydrides

- Metal hydrides are the most relevant of hydrogen storage. The thermodynamics of H_2 adsorption / desorption (enthalpy) govern their temperature and pressure.
  - No need for compressors and volumes are considerably lower than real gas law requirements
  - A lower enthalpy hydride (AB_5-type alloy) in conjunction with a moderate capability pressure (<100 bar) buffer tank is an optimum from engineering standpoint.
- For a 2 kWh of energy, 85.5 grams or 42.4 moles of H_2 and 21.2 moles of O_2 would be required.
  - The initial fuel requirements be part of the launch package with supplemental fuel harvested from the atmosphere.
  - The mass of the $MmNi_5$ (Mm is misch metal, which is a naturally occurring alloy of rare earth metals) would be 4.6 kg the volume is ~0.9 liters.
  - Absorption/desorption kinetics are rapid at 300°C.
  - Requires 21 moles of oxygen at 65 km altitude. For a pressure of 100 bar, a container would require an interior volume of 4.2 liters.
- The system is anticipated to be encased in a Titanium shell that has the stability against high pressure, high temperature and H_2SO_4

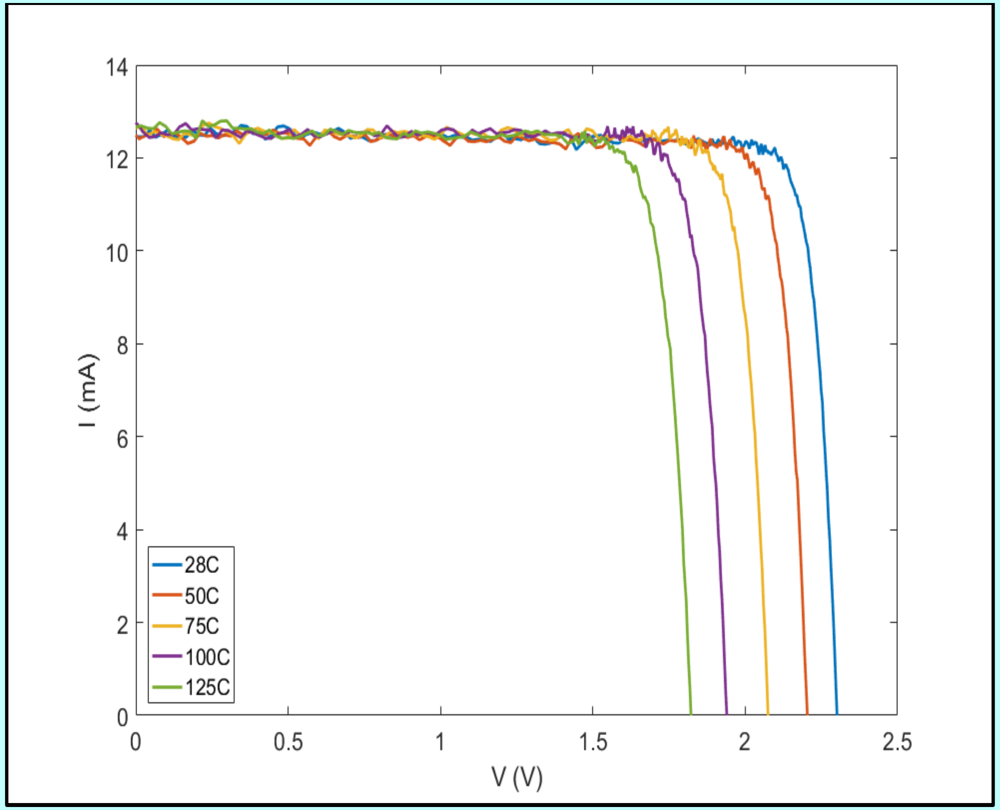


van't Hoff plot

$$\ln P = \frac{\Delta H}{RT} - \frac{\Delta S}{R}$$

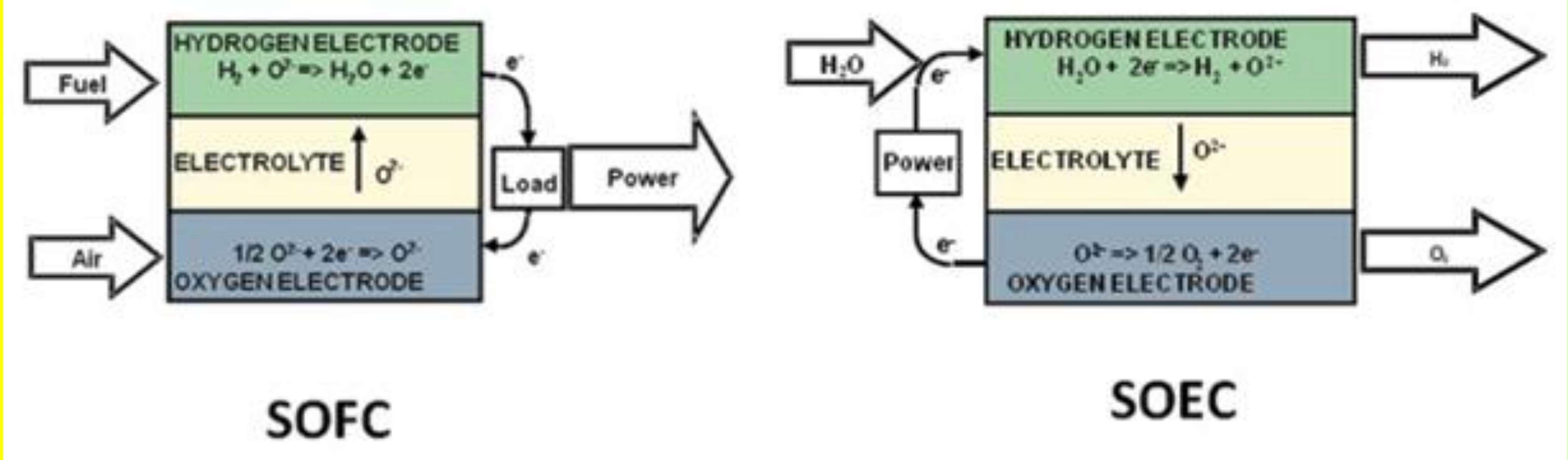
High-Temperature Tolerant Solar Cells

- Conventional triple junction solar cells, GaInP2/GaAs/Ge with an efficiency of ~30% will be used. These solar cells need to have adequate survivability at the high temperatures (300-350 °C) prevalent at low altitudes (10-15 km) in non-operating mode.
- NASA-GRC has been developing solar arrays for high temperature near-sun operation with the goals of improved efficiency at high temperature and also improved lifetime at high temperature.
- JPL has started developing high temperature tolerant solar cells under NASA's HOTTECH Program, using wide bandgap materials, since the higher voltage of wide bandgap solar cells results in less degradation.
    - For example, Si solar cells (1.1 eV) lose ~ 0.45% of their power per degree C increase in operating temperature. GaAs cells (1.4 eV) lose about 0.21% per °C.
- For the VIP-INSPR, however, it is the lifetime that is crucial, since power at low altitudes (high temperatures) is provided by the fuel cell.



H_2/O_2 Solid Oxide Fuel Cell (15 km)/Electrolyzer (55-65 km)

- A reversible solid oxide fuel cell (RSOFC) is a device that can operate efficiently in both fuel cell and electrolysis operating modes. Thus, in the fuel cell mode, an RSOFC functions as an SOFC, generating electricity by electrochemical combination of a fuel (hydrogen) with oxygen. In the electrolysis mode, an RSOFC functions as an electrolyzer (solid oxide electrolysis cell or SOEC), producing H_2 and O_2 (from H_2SO_4 or H_2O) . A SOFC system would need to be heated to ~800 °C continuously to operate, and thus would be well insulated from the rest of the spacecraft to avoid overheating the electronics and other systems.



Operating Principles of an RSOFC (written for hydrogen fuel in SOFC mode and steam electrolysis in SOEC mode).

Venus Altitude Cycling Balloon

The Vega Balloons (Example)

- 3.4 meter diameter balloon and a gondola, suspended by a 13 meter long tether.
- The total mass of the deployed balloon probe was 21.5 kg: 12.5 kg for the balloon and tether, 6.9 kg for the gondola, and 2.1 kg of helium.
- The balloon was made of a PTFE cloth matrix coated with Teflon film and filled with helium to 30 mbar overpressure.
- Diffusion of helium was slow enough that the balloon would outlast the probe battery lifetime, losing less than 5% of its helium and 500 meters of altitude.
- A rigid balloon using Ti is another possibility but it would need to be smaller than booster vehicle (non-spheroidal shape possible?)
- $\mathrm{Mass}_{payload} = V_{balloon} \times (r_{atm} - r_{H2}) - \mathrm{Mass}_{balloon} - \mathrm{Mass}_{BOP}$

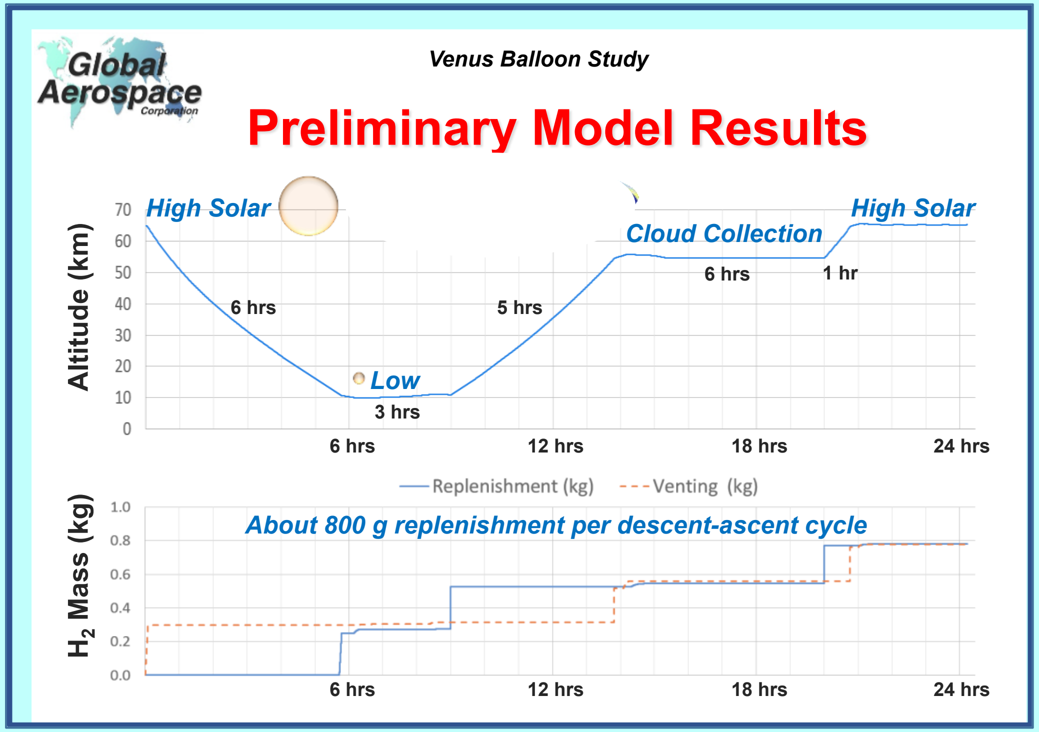
Preliminary (VIP-INSPR) Balloon Design

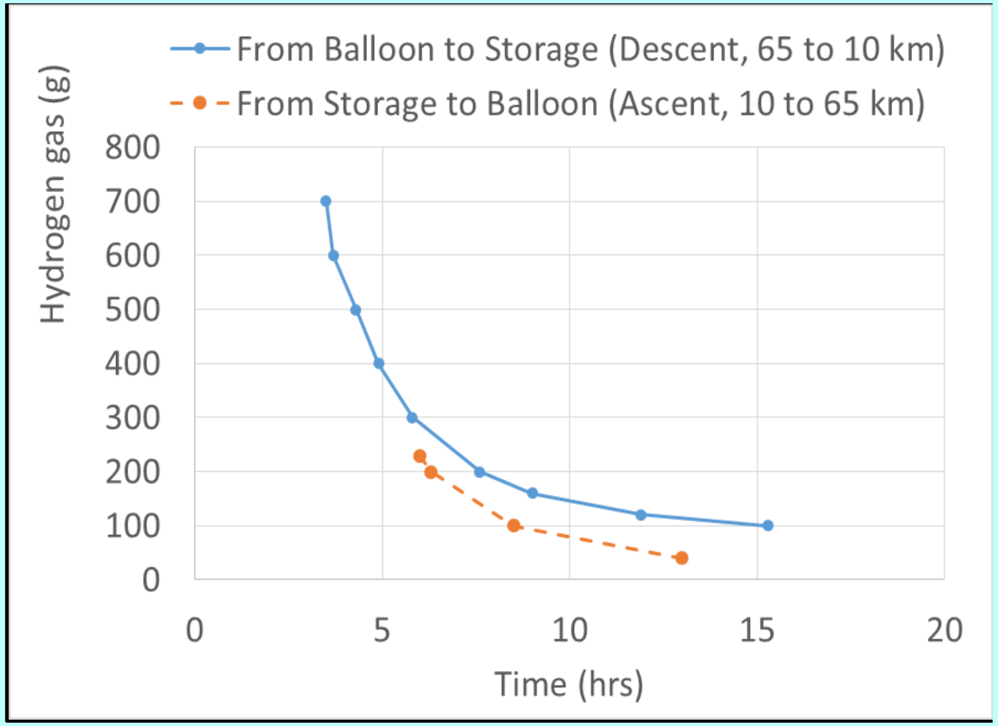
- A balloon system design that can cycle in the following altitude range of 15 to 65 km (goal)
- The Suspended payload mass is 150 kg;
- The balloon system could be a single or dual balloon design
    - Single, near-spherical zero pressure balloon to keep balloon design simple and lightweight
    - Post-entry deployment with use of internal lines to reduce loads on envelope.
    - Initial inflation with hydrogen to avoid mixing gases
    - Cycling and control of altitude by means of buoyant gas venting and filling, and
    - Simple control system to descend, ascend and maintain desired altitudes

- Balloon Assumptions:
    - Temperature extremes of 380°C at 10 km & –33°C at 65 km
    - Polyimide (e.g. Kapton®) or Polybenzimidazole (PBI) Film.
    - Must meet packaging requirements with sulfuric acid cloud droplets (85% solution). Vapor Deposited gold or SiO_2 for protection
    - Envelope material and seaming approach must withstand Venus environment; Polymer resin bonded seams or Vapor Deposited coated seams
    - Envelope mass: 16.6 kg and volume: 11.8 m (at 65 km) and 1.1 m (at 10 km)
    - Envelope base needs to support load of suspended mass
    - Venting and fill features

- Carried out by our collaborators Kerry Nock and Peter Ngo at the Global Aerospace Corporation in Pasadena, CA

Preliminary (VIP-INSPR) Balloon Design





Required lifting gas transfers for ascent and descent

- Altitude cycling and control is achieved by means of buoyant gas storage.
- Taking as little as 200 g of H_2 gas from the envelope and storing it at much higher density than ambient (at lower altitudes), results in negative balloon buoyancy that causes the balloon to descend to 10 km in just over 7 hours.
- Withdrawing smaller amounts from the balloon results in longer descent times.
- Re-filling the balloon with stored gas allows the balloon to return to positive buoyancy and ascend.
- Making slight adjustments near the bottom and top of the altitude range can enable quasi-altitude stability operation.

  - Carried out by our collaborators Kerry Nock and Peter Ngo at the Global Aerospace Corporation in Pasadena, CA

Preliminary (VIP-INSPR) Balloon Design

Global Aerospace Corporation

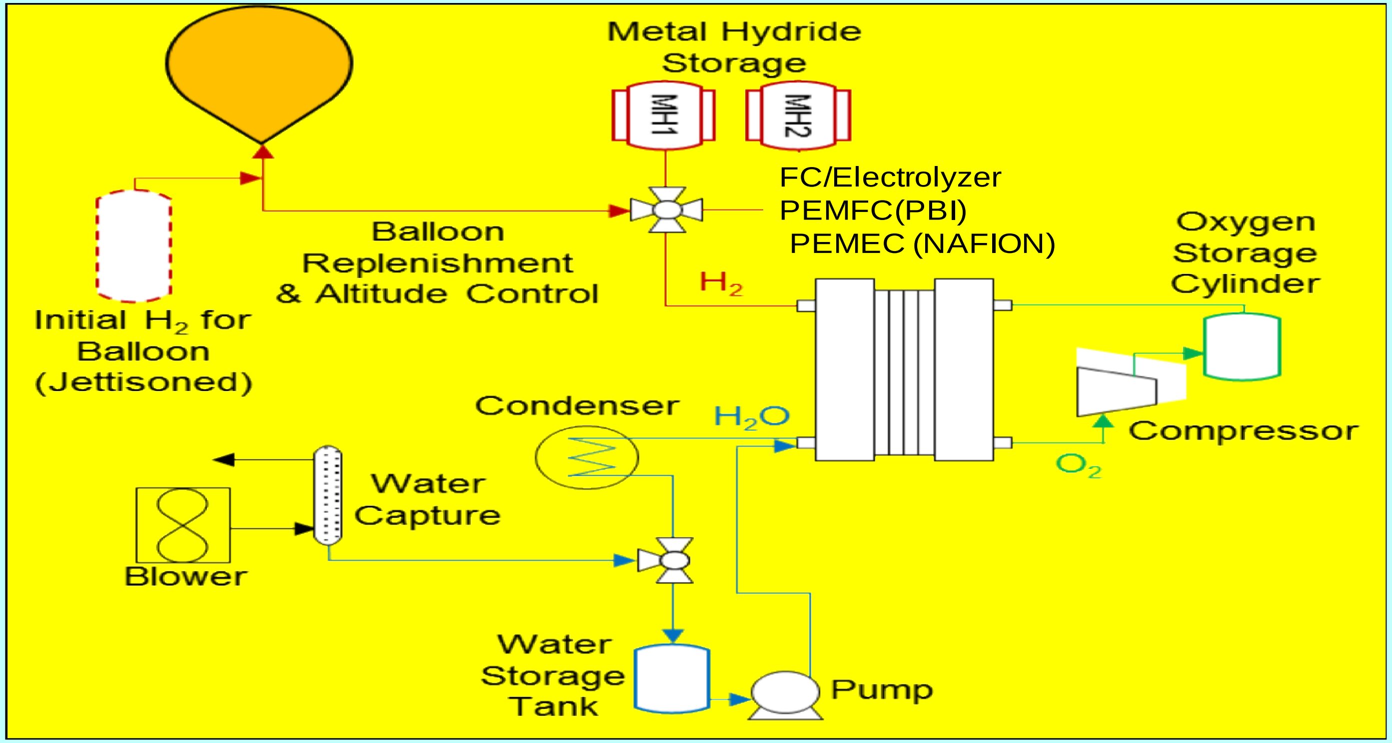
Venus Balloon Study

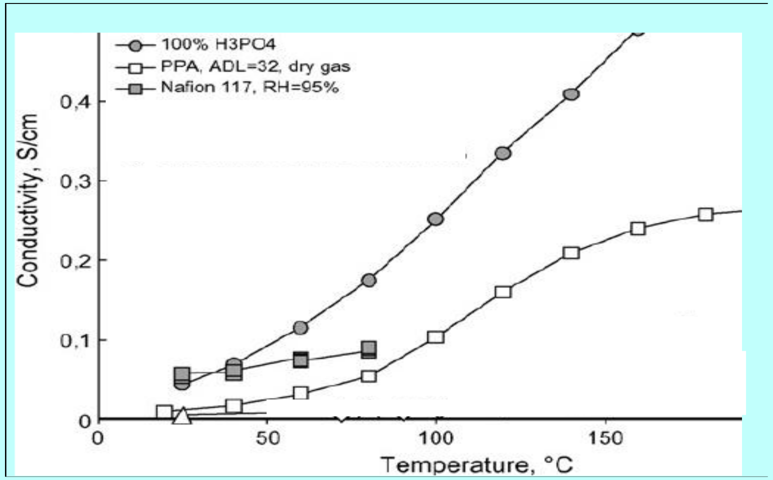
Initial Design Comparison

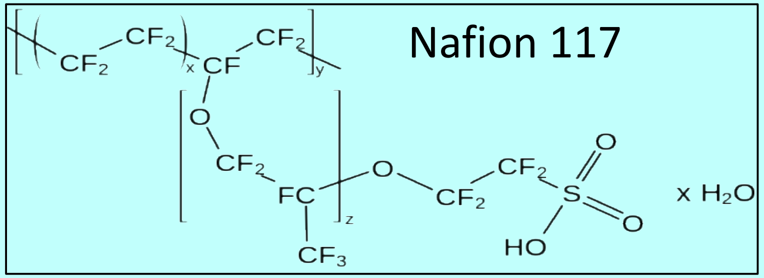
	VIP-INSPR	Vega aerostats
Type	ZPB	Spherical SPB
Gas	8.1 kg Hydrogen	2.1 kg Helium
Volume	865 m^3	20.6 m^3
Diameter	11.8 m (65 km) 1.1 m (10 km)	3.4 m
Envelope Material	1 mil coated Kapton	Teflon laminate
Envelope Density	37.8 g/m^2	~300 g/m^2
Envelope Mass	16.6 kg	12.5 kg (includes 13 m tether)
Payload Mass	150 kg	6.9 kg
Design Altitude	10 – 65 km	54 km

- Carried out by our collaborators Kerry Nock and Peter Ngo at the Global Aerospace Corporation in Pasadena, CA

Modification of the VIP-INSPR for Higher Altitudes (55-40 km)







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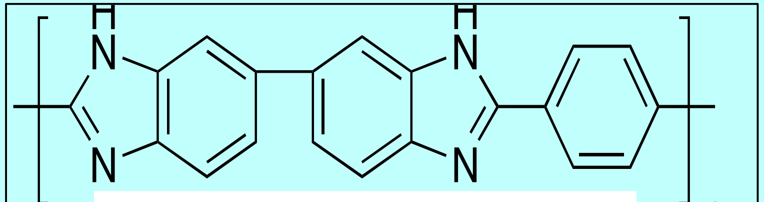

Polybenzimidazole (PBI)

para-PBI

- A novel architecture, combining fuel cells with two different polymeric membranes, functioning as fuel cell for power-generation at low altitudes and as electrolyzer for fuel-regeneration at high altitudes, in conjunction with a reversible MH for H2 storage and a PV array.
- Based on the maturity of these component technologies, this power system will enable rapid maturation and demonstration, which may lead to subsequent development and infusion in a Venus aerial mission.

On-going Studies (in Phase II)

- Our Phase 1 studies show that the VIP-INSPR concept is credible and viable.
- We are continuing our studies to demonstrate the viability of VIP-INSPR and establish its maturity for incorporation into future Venus discovery missions.
  - Demonstrate the compatibility and performance of the component technologies, such as SOFC, Metal hydrides, solar array and H_2-based balloon in Venus environments by tests or analyses.
  - Determine the hydrogen leak rates from the balloon (at high temperature) to assess the need for fuel replenishment from in-situ resources.
  - Complete preliminary designs for the Reversible SOFC, Electrolysis cell, hydrogen storage bed.
  - Understand the interactions and verify the compatibility of component technologies at the systems level, e.g., transfer of H_2 in and out of the balloon into the H_2 storage system.
  - Estimate the mass and volume of the subsystems for a VIP-INSPR having 150 kg of payload and 2 kWh of energy storage at low altitudes (10-15 km).
  - Understand through modeling the possible trajectories of the Venus probe in the context of the strong wind currents prevalent.
  - Explore options for the infusion of VIP-INSPR into future Venus Discovery missions with variable altitude aerial platforms.

Acknowledgements

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